Actions on structures exposed to fire

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EC 1: Actions on Structures Exposed to Fire

EC 1: Actions sur les structures exposées au feu

EC 1: Brandbelastung von Tragwerken

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SUMMARY

Chapter 20 of the Eurocode on Actions specifically deals with actions on structures exposed to fire. It is intended for use in conjunction with the parts on structural fire design of the material orientated Eurocodes 2 to 6. A first draft was presented in 1990. Based on various comments, the draft has been improved and should be finalized at the beginning of 1993. This paper deals with some practical aspects of the 1990 draft and some future developments are highlighted.

RESUME

Le chapitre 20 de l'Eurocode sur les actions traite spécifiquement des actions sur les structures exposées au feu. Il est destiné à un emploi conjoint avec les éléments traitant du projet des structures sous l'effet des incendies des Eurocodes 2 à 6, consacré aux matériaux spécifiques. Un premier projet a été présenté en 1990. Il a été successivement amélioré sur la base de commentaires et un projet final devrait être établi au début de 1993. Cette présentation traite d'aspects pratiques du projet de 1990 et des développements possibles.

ZUSAMMENFASSUNG

Kapitel 20 des Eurocodes über Einwirkungen behandelt ausschliesslich die Brandbelastung von Tragwerken. Es ist für die gemeinsame Anwendung mit den Teilen über Brandbemessung in den werkstoffspezifischen EC's 2 und 6 gedacht. Ein erster Entwurf wurde im Juni 1990 vorgestellt. Aufgrund verschiedener Stellungnahmen wurde er überarbeitet und sollte Anfang 1993 in der Endfassung vorliegen. Der Beitrag behandelt einige praktische Aspekte der Fassung 1990 und beleuchtet zukünftige Entwicklungen.

1. INTRODUCTION

Chapter 20 of the Eurocode on Actions specifically deals with actions on structures exposed to fire. It is intended for use in conjunction with the parts on structural fire design of the material orientated Eurodes 2 to 6. A first draft was presented at a symposium in Luxembourg in June 1990 [1]. EC member states have been invited to send in their comments. Redrafting has started in autumn 1991. Versions for SC voting should be available by the end of 1992 or the beginning of 1993.

This paper deals with some practical aspects of the 1990 version of EC-Actions, chapter 20 [1]. Also some future developments will be highlighted.

2. GENERAL FEATURES

The following general features apply:

- accidental situation;
- fire situation;
- post-fire situation.

A direct consequence of the assumption that fires may be considered as accidental situations is that simultaneous occurrence with other (independent) situations need not to be considered.
Clearly, fire constitutes the dominant action in a fire design. Nature and extention of the fire should therefore be identified. As far as the nature is concerned, only fully developed fires inside the buildings are considered. If a building is divided into fire compartments, fire exposure is only in one compartment at a time. From this rule, the way in which building components are exposed (from one side only, or from more sides) can be determined.
In view of the generally accepted objectives of designing for fire (i.e. limiting risk with respect to life and property loss as a direct result of fire), [1] does not consider any post-fire situations.

3. THERMAL ACTIONS

3.1 General

In order to provide optimal guidance for practical application, in [1] the generally accepted design procedures for fire design are taken as a starting point. I.e., a central role is for the standard fire approach and the related grading system in terms of fire resistance. Using an analytical approach - as specified in EC 2 to 6 - rather than an experimental one, renders a relatively simple possibility to achieve unambiguous results. This is a key element in standardization. On the other hand one should realize that the standard fire concept is very global and that solutions are often far from reality. Under circumstances, economic building design requires therefore a more nuanced analysis. For this reason, in [1] the door is opened for more physically based, differentiated approaches as well. Details of these approaches are intended to be given in the appendices. In [1], these appendices are only outlined regarding their possible scope and contents in order to collect options during the national inquiry to the extent to which the various items should be pursued for further incorporation.

3.2 Standard fire exposure

For the gas temperature time relationship used in standard fire conditions, refer to Fig. 1. It is emphasized that the temperature curve is not sufficient to define fire exposure conditions. Also the (radiative and convective) heat transfer characteristics from the environment to the exposed members should be specified. The assumptions made in this respect in [1] are presented in Fig. 1 as well. It is noted that both the standard fire curve and the heat transfer characteristics have a conventional rather than a physical meaning.

3.3 Compartment fire exposure

Fully developed compartment fires (i.e. fires characterized by full involvement of all combustible material) are taken as a basis for fire engineering design. During the last decades, various calculation models have been developed for the calculation of the gas temperature in such fires. See for example [2,3]. The models are based on the heat & mass balance for a given situation and generally take into account the effect of ventilation conditions, fire load density and thermal properties of the construction elements surrounding the fire compartment. Extensive experimental research has been carried out to verify the models and a reasonable agreement between theory and experiment can be achieved. See Fig. 2.

The calculations result in quite nuanced relationships between gas temperature and time. For practical use such curves are felt to be too cumbersome. Moreover, the models generally take only physical parameters into account, i.e. any human interference with the fire process is excluded. It is suggested, therefore, to conventionalize the calculated fire curves to "design natural fire curves". For a set of such design curves, based on the model described in [3], refer to Fig. 3 [4,6]. For other design curves, see [2,5]. Note that specification of the heat transfer characteristics and the field of application is necessary.

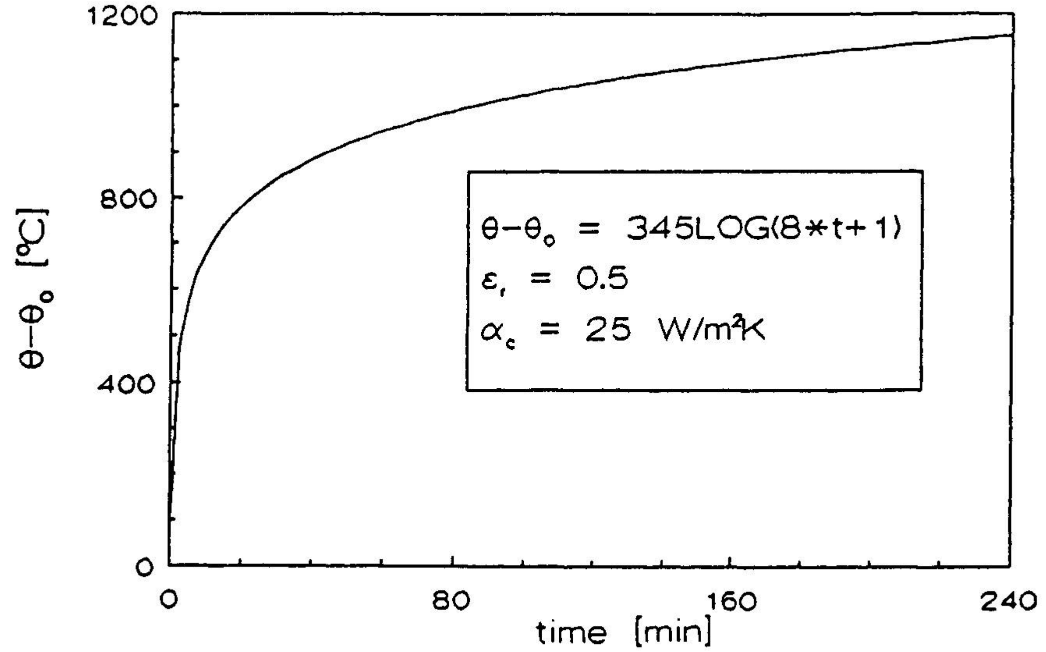


Fig. 1: The standard fire curve and associated heat transfer characteristics

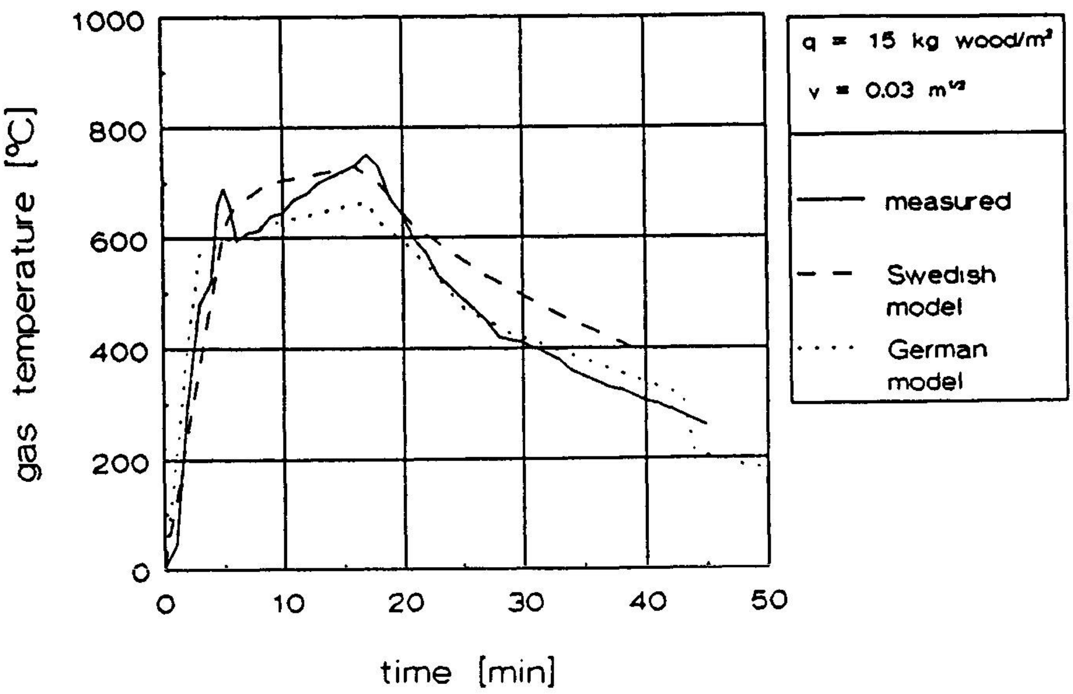


Fig. 2: Measured and predicted compartment temperatures (fire load density 15 kg wood/m², opening factor 0.03 m$^{1/2}$).

3.4 Practical implications

Using natural fire exposure together with the standard fire concept in one code, brings a question of consistency with regard to required levels of safety. In an approximate way, this problem has been solved by using the concept of effective fire duration. The effective fire duration (t_{eff}) is a quantity which relates compartment fire conditions to standard fire conditions;

$$t_{eff} = q \cdot w \cdot c \cdot \gamma \cdot \gamma_n \qquad (1)$$

with:

q = fire load density
w = ventilation factor
c = conversion factor
γ, γ_n = safety, adaption factor

Alternatively, one can also express the fire load density in terms of effective fire duration. An effective fire duration equal to the required fire resistance gives the so-called nominal fire load density (q_n):

$$q_n = w_{c,\gamma} \cdot t_{f,r} \qquad (2)$$

with:

$t_{f,r}$ = required fire resistance (= t_{eff})
$w_{c,\gamma}$ = $1/(w \cdot c \cdot \gamma \cdot \gamma_n)$

By way of convention it is postulated that an assessment based on standard fire exposure and a certain required fire resistance gives rise to the same safety level as an assessment based on compartment fire exposure and a corresponding fire load density

4. MECHANICAL ACTIONS

4.1 General

Mechanical actions cover:

- actions from normal conditions of use;
- indirect fire actions.

Indirect actions may occur as result of restrained thermal expansion and depend on the temperature development in the structural system and differences in stiffness. Indirect actions may develop in both isostatic and hyperstatic systems. A typical example of indirect actions due to fire are temperature induced stresses due to non-uniform temperature distribution over the cross section. These will occur in the centrically loaded concrete filled HSS-column, exposed to fire from all sides, presented in Fig. 4. For a qualitative presentation of the temperature distribution over the cross section and the pattern of additional stresses due to restrained thermal elongation, refer to Fig. 4a. The effect on the load bearing capacity is exemplified by the two buckling curves presented in Fig. 4b. Both curves are calculated for reinforced, concrete filled HSS columns (□ 300 x 300 x 7 mm), after 90 minutes standard fire exposure [7]. The solid curve includes the effect of the thermal induced stresses; this effect is ignored in the dashed curve. Depending on the buckling length, significant differences appear to occur.

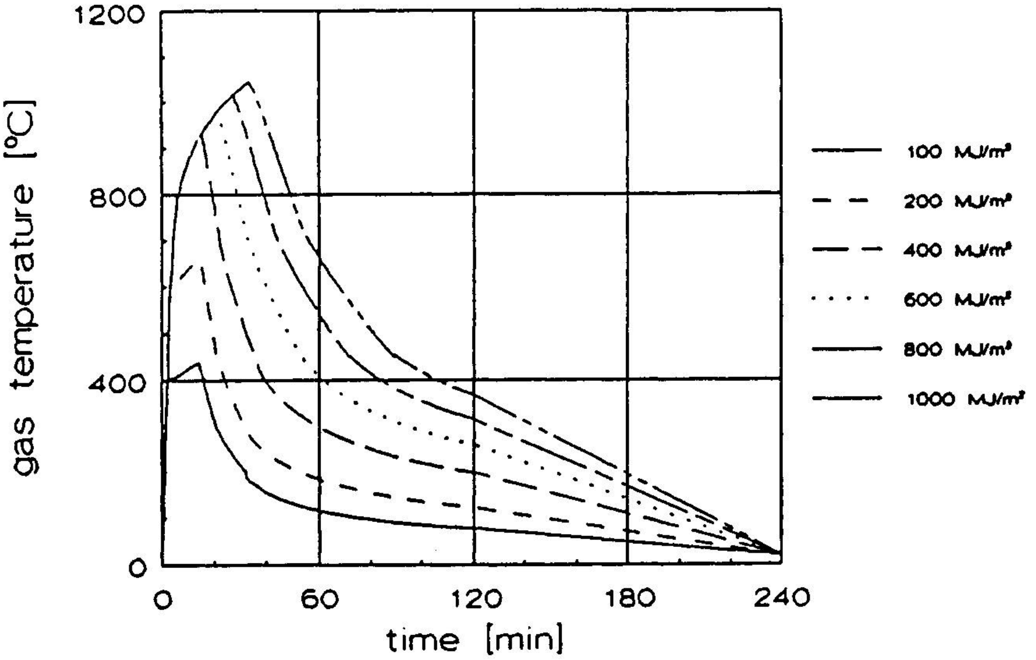


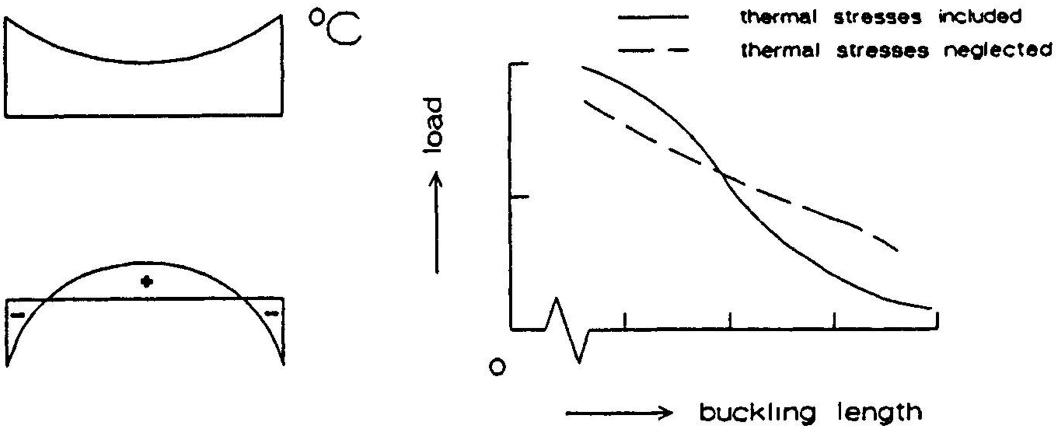
Fig. 3: Design natural fire curves for an opening factor of 0.06 [$m^{1/2}$] and fire loads in the range of 100 to 1000 MJ/m^2.

4.2 Combination rule

In symbolic form the combination rule for action effects for room temperature conditions (so-called fundamental combination rule) reads [8,9]:

$$E_d = \gamma_G \cdot G_k + \gamma_{Q,1} \cdot Q_{k,1} + \Sigma\, \gamma_{Q,i} \cdot \psi_{0,i} \cdot Q_{k,i} \qquad (3)$$

with:



(a) distribution of temperature and thermal stresses (schematic)

(b) buckling curves at elevated temperatures

Fig. 4: The effect of restraint of thermal elongation on the load bearing capacity of fire exposed concrete filled steel columns.

E_d : design value of effect of actions for normal conditions,
γ_G : partial safety factor for permanent actions,
G_k : characteristic value of permanent actions,
$\gamma_{Q,i}$: partial safety factors for variable actions,
$Q_{k,1}$: characteristic value of the main variable actions,
$\psi_{0,i}$: combination factor for variable loads,
$Q_{k,i}$: characteristic value of the other variable actions,

The corresponding rule for the accidental situation reads [8,9]:

$$E_{d,acc} = G_k + \psi_{1,1}\cdot Q_{k,1} + \Sigma\, \psi_{2,i}\cdot Q_{k,i} + A_d \qquad (4a)$$

where:

A_d : the design value of the accidental action,
$\psi_{1,1}\cdot Q_{k,1}$: frequent value of main variable load,
$\psi_{2,i}\cdot Q_{k,i}$: time average of other variable loads.

Safety factors γ_g and γ_q are set to unity to account for the rare occurrence of an accidental situation. The main variable action is represented by its frequent value, the other variable actions are combined using their quasi-permanent (time average) values. These values account for the fact that it is unlikely that (all) variable actions will attain their characteristic value during the short duration of the accidental action.

In traditional fire testing, generally a "service load" was applied, resulting from the self weight of the construction and imposed loads. This is more or less equivalent to $G_k + Q_{k,1}$, i.e. no distinction is made between structures with small and large portions of self weight, implying a lower safety level for the latter. Hence, applying Eq. (4a) for fire design will give a more uniform safety level. With regard to the average safety level, it should be noted that, traditionally, indirect actions from fire exposure in terms of $A_d = A_{d,ind}$ were not considered.

The indirect actions are related to the fire, hence the corresponding combination factor obviously equals to unity.

It is suggested to use the accidental combination rule, for fire design with frequent and quasi-permanent values as specified for room temperature design [8,9]. With adopted notations the rule reads:

$$E_{d,f} = G_k + \psi_{1,1}\cdot Q_{k,1} + \Sigma\, \psi_{2,i}\cdot Q_{k,i} + A_{d,ind} \qquad (4b)$$

From tentative calculations it follows that the combination factors in case of fire do not differ significantly from those specified for room temperature design [9]. In view of the uncertainties involved in both the physical and the statistical model, it has been decided to use room temperature values for the combination factors in the above combination rule. These depend on the category of the area under consideration and may vary for the main variable action in offices etc. between 0.5 and 1. See also [8].

4.3. Practical implications

Application of the above combination rule requires a complete global analysis for fire design. An important simplification may be achieved as follows:

If indirect actions due to fire do not occur or are negligible and only one variable (leading) action needs to be taken into account, the ratio between the design action effect for the fire situation and the corresponding value for the room temperature design follows from:

$$\frac{E_{d,f}}{E_d} = \frac{r + \psi_1}{\gamma_G r + \gamma_Q} \qquad (5)$$

with:

$r = G_k/Q_k$
E_d, $E_{d,f}$, G_k, Q_k, ψ_1, γ_G, γ_Q: as defined under 4.2.

For values for the partial safety factors as suggested in [10] (i.e. $\gamma_G = 1.35$ and $\gamma_Q = 1.50$) and a calibration case defined by:

$\psi_1 = 1.0$ representative for imposed loads, area category D (i.e. public premises susceptible to overcrowding and accumulation of goods), this rendering the traditional service load,
$r = 1.0$ practical value for r, valid for heavy weight structures (e.g. normal weight concrete)

equation (5) yields:

$$E_{d,f} \approx 0.7\, E_d$$

This value is suggested in [1] of the Eurocode on Actions.

According to Eq. (5), the ratio between the design value for the action effect in case of fire and the corresponding value for normal conditions of use, depends, for a given set of partial safety factors, on two parameters only:

- the ratio between permanent and the main variable action ($= r$);
- the frequent value factor for the main variable action ($= \psi_1$).

In Fig. 5, $E_{d,f}/ E_d$ is presented as function of r (= G_k/Q_k) and some practical values for ψ_1, taking into account partial safety factors for actions as suggested in [10] (i.e. γ_G= 1.35 and γ_Q= 1.50). It follows that, within a practical range for r -between, say, 0.5 and 1.5- the variation in $E_{d,f}/ E_d$ is significant.

For:

r ≈ 0.5, (which is representative for steel structures)

and

ψ_1 = 0.5 (which is representative for area category A, e.g. dwellings, offices, hotels)

it follows:

$E_{d,f} \approx 0.45\ E_d$

Hence, under the given circumstances, the design value for the action effects may taken significantly smaller taken than the global value specified in the 1990 draft of chapter 20 of the Eurocode on Actions [1].

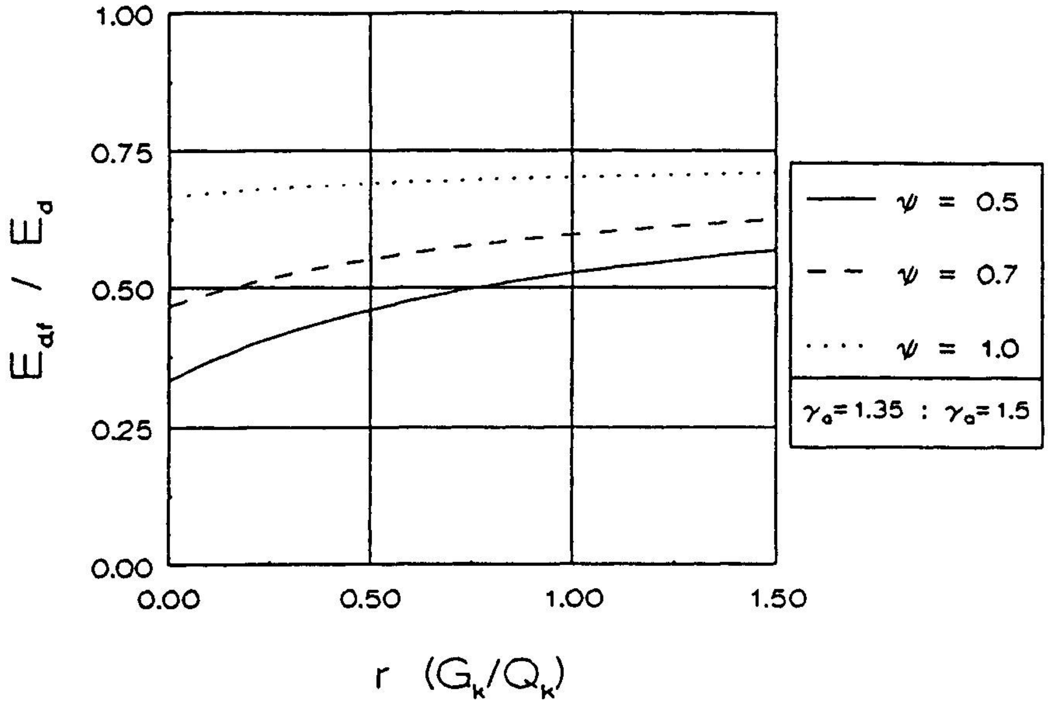


Fig. 5: Ratio between design effect of actions in case of fire and the design effect of actions at room temperature, as a function of the ratio between the permanent and main variable action, for given values of the partial safety factors (γ_G=1.35; γ_Q=1.5).

5. DEVELOPMENTS

As mentioned already under 1, work is in progress to evaluate and incorporate obtained comments on the 1990 draft of the fire part of the EC-Actions. Main modifications will be with respect to the thermal actions. Important items are:

* improved definition of the thermal actions, i.e. in terms of net heat flux to structural members, considering thermal radiation and convection from and to the fire compartment;
* specification of various sets of nominal time temperature curves i.e. (1) the (ISO) standard time curve, (2) a Hydrocarbon curve, (3) an external fire curve;
* specification of simple fire models for compartment fire exposure and external members, where appropriate in the form of design natural fire curves;
* reconsidering the suggested relationship between the action effects for room temperature design and for the fire situation; cf. discussion under 4.3.

More advanced fire modelling will be incorporated only in a later stage, i.e. not within two years from now.

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